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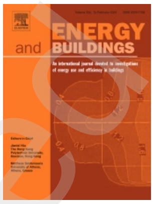

Low-carbon building design: probabilistic method for the relationship between carbon footprint and building typology, in the Mediterranean climate zone

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ABSTRACT

The research develops a methodology aimed at the correlation between building type and Embodied Energy (EE) and Carbon (EC). The interest in this research area arises, as a response to the current political-environmental scenario, from the opportunity to combine technological design and reduction of CO2e emissions. The objective is to determine, among the building types prevalent in the Mediterranean coastal area, the one that, due to its formal characteristics, has the least impact in terms of carbon footprint. The technological characterization of the selected building types (detached house, townhouses, multi-storey building), from a coastal area in southern Italy, is essential for the application of the methodology and the subsequent comparative approach. The social contribution of the study is to determine new indicators, to be applied in urban planning, in order to characterize city expansion with low carbon impact.

1. Introduction

Anthropogenic activities that lead to increased carbon emissions are recognized as a primary driver in climate change. The construction sector is responsible for consuming about 20 percent of the total energy supplied worldwide and 35 percent of the associated greenhouse gas emissions. In Europe, these percentages stand at 40 percent of energy consumed and 36 percent of greenhouse gases [1]. ISPRA report 363/2022 [2] shows that between 1990 and 2020 the residential sector will experience an increase, in terms of energy consumption, of about 20 percent compared to other productive sectors. The energy consumption of a building, over its life cycle, is composed of an operational energy (OE) rate and a gray or embodied energy (EE) rate. The use phase (OE) represents the most emission-intensive stage, so it focused the interest of early energy efficiency studies.

According to Azari R. and Abbasabadi [3], EE accounts for 10-12% of the total life-cycle energy consumption of conventional residences and 31-46% in those adopting higher levels of insulation, a further survey of the literature on the variability of the relationship between EE and EO, predicts that it will mutate further by 2050. In that study, it is assumed that the increase in EE from 26% to 35% (assuming a renewal rate of existing buildings from 1.4 to 1.9%) may be matched by a decrease in EO% between 19% and 46%.

The importance of investigating new design strategies, aimed at reducing EE, stems from the observation that, over the past twenty years, the transition from an energy 'conventional' building to an energy efficient 'NZEB' building has shown the reversal of the OE/EE ratio with a consistent reduction in OE, and a significant increase in EE, in the overall energy balance of a building (Fig. 1).

Crowther [5] defines embodied energy as “the total energy required in the creation of a building, including direct energy used in the construction and assembly process and indirect energy, which is required to manufacture building materials and components”. Guan et al. [6] point out that, in China, a significant increase in Greenhouse Gas Effect has resulted from construction activities resulting from rapid and intensive urbanization. However, it is difficult for conventional life cycle assessment (LCA) models to accurately quantify the embodied energy of a building. This study develops a hybrid input-output (IO)-based LCA model, where sensitivity analysis is used to identify key linkages between sectors that significantly affect building embodied energy.

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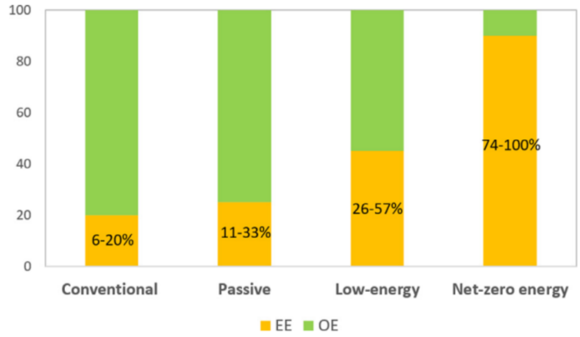

Fig. 1. Significance of EE and OE in the life cycle energy use of residential buildings. (source: Chastas et al.[4]).

2. State of the Art

For at least a decade now, scientific studies have focused on strategies for sustainable building design, low Energy and Embodied Carbon (EE, EC). Pomponi et al. [7] identified a number of strategies to mitigate embodied carbon; these include the use of materials with lower EE and EC, reduction, reuse, and recovery of intensive building materials, renovation of existing buildings, and more efficient construction techniques. Some studies have focused on the 'influence of building height. The study by Gan et al. [8] evaluates the effects of material choices, recycled content, building heights and structural forms on the EE of high-rise buildings. The results show that compared with composite and ca buildings, the steel building has 50%-60% less total weight, but produces 25%-30% more EE because large amounts of carbon-intensive steel sections are required to build the horizontal action resistance system. However, if more than 80% of the steel is reused/recycled, the EE of the steel building, the gap with the concrete framed building can be minimized. Foraboschi et al. [9] based their study on four buildings with different heights, from 20 to 70 stories, located in different nations, but with common structural scheme, central core and reinforced concrete or steel frames. They demonstrated a double exponential dependence between height and embodied energy: the amount of material and the height premium. However, they also showed that a structure with lower weight does not necessarily imply less EE and that, for the same material quantity, the typology of material greatly influences the final result. Waldron et al. [10] investigated different urban scenarios, characterized by the presence of three building typologies: high-rise, mid-rise and low-rise buildings, using a comparative approach. This study showed that it is easier to design a building to reduce its operational energy and not its embodied energy; in particular, the medium building category was shown to be the most predisposed to energy efficiency, while for EE the scenarios are less clear and seem to depend on the intended uses. Han et al. [11] devised a simplified, three-step hybrid method applied to the E-town case study in Beijing. The first step, the collection of data from the Bill of Quantities (BOQ), quantifies the labor of all construction engineering inputs, with reference to the quantity and price of each material; the second is the identification of the production sector and the embodied energy intensity of each input; and the third is the calculation of the total embodied energy consumption. Basbagill et al. [12] propose a neighborhood scale EE calculation model of a group of buildings with the following input parameters: no. of buildings, no. of floors, building footprint size and window-wall ratio. The calculation is automated using BIM software integrated with LCA, energy simulation and sensitivity analysis, guiding designers toward EE reduction by varying materials and thicknesses on a basis of comparable buildings in terms of shape and gross floor area. Davila and Reinhart [13], on the other hand, proposed a model based on the representation of buildings in a 3D CAD environment, from which to extrapolate the quantities of technological units such as roof, exterior walls, ground floor, and then link them to embodied energy factors. The simulation was carried out on three different urban scenarios, as a function of floor area occupancy ratio (SOR), demonstrating how an increase in SOR generates an increase in EE and that, for very high values of SOR, the building form is irrelevant. With reference to the neighborhood scale, Trigaux et al. [14] started by expanding the system boundary, taking into account the entire life cycle, both of the buildings and the included urban infrastructure. The study was conducted on four neighborhoods, consisting of single houses, semi-detached houses, townhouses and multi-family buildings. The results, in terms of emissions, show that single houses have a 50% higher impact than townhouses and 30% higher impact than condominiums. However, this study refers to abstract neighborhood models, not actual case studies. Giordano et al. [15] prepared a study on Embodied and Operational Energy for NZEB building design, with reference to materials, building systems and glazing ratio (WWR). This paper, too, pointed out the difficulty of balancing Embodied and Operational Energy and how, although they place the WWR between 30% and 50% (resulting in a decrease in the mass of the envelope), the EE increases due to the energy used in the production of glass, aluminum, and wood. Garzedi et al. [16] proposed an embodied carbon estimation tool for houses in Malaysia, based on gross area, length-to-width ratio, volume, and weight, showing that, for the same building system, EE is highly dependent on form parameters, however, a detailed analysis of the specific effect of each input parameter is not provided. Lotteau et al. [17] devised a methodology aimed at relating Embodied Energy to the morphology of the two most common residential building typologies on the French territory, block and terraced. Even in this study, however, the focus was divided into structural and morphological aspects, providing a comparison between them. The methodology developed by Natanian et al. [18], with reference to the Mediterranean climatic and urban context, consists of a parametric typological analysis, automated using Grasshopper with a total of 1920 iterations. For each iteration, the performance effects of both building (i.e., typology, window-wall ratio, and glazing properties) and urban design parameters (i.e., building spacing, floor area ratio, and orientation) were evaluated for residential and office uses. The correlation between the form factor and energy load matching index were established, as well as the benefits of the courtyard typology in terms of energy balance with its challenging daylight performance. These results demonstrate the potential of this workflow to highlight design trade-offs between form considerations and environmental performance on the part of designers and thus provide a new way to bridge the performance gap between buildings and their urban environment.

The analysis of the state of the art showed a predominant focus on the contribution of materials and building system in estimating embodied energy and carbon. Relative to the influence of building form and typology, no study has estimated its magnitude, incidence, either at the scale of the individual building or at the scale of the neighborhood, through simulations, without analyzing real case studies. The main critical issue highlighted by the authors was mainly the difficulty in finding energy data, which were generally valid and easy to apply, at

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any scale and for all objects of analysis. The outcome of this study will be the relationship between embodied energy/carbon and residential building typology, a topic that, at present, is a scientific gap. The developed method presents future opportunities: to limit emissions and embodied energy to an embryonic morphological design level; to apply the method to any building typology and technological characterization; to expand the scale of application of the method from the individual building to the neighborhood scale; and to relate the analyzed shape parameters to the urban parameters of land use planning tools.

3. Tools And Methods

The methodological development is aimed at combining the following instances: a) analysis of building typological and constructional characters; b) method of deduction of energy and emission data. The methodology consists of 8 steps: 1) selection of case studies; 2) decomposition of typology buildings into technological units and functional elements (according to UNI 8290-1:1981); 3) characterization of technological units and functional elements; 4) quantification of functional elements; 5) calculation of embodied energy and carbon (cradle to gate scope); 6) shape parameters; 7) sensitivity analysis of independent shape parameters; 8) evaluation of dependent shape parameters.

3.1 Case studies select

The identification of significant building typologies, for the purposes of methodological development, required two choices relating to: intended use and geo-morphological scenario. The intended use identified, by virtue of greater interest and notable variability and frequency, is residential. The hypothesized geo-morphological scenario is the coastal one typical of southern Italy, where the residential urban fabric is characterized by the prevalent presence of three building typologies: detached house, townhouses and multi-storey building.

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3.2 Subdivision of the building into technological units

In order to study each of the three typologies, the building was looked at as a set of structural and non-structural parts, strongly related to materials, the primary source of energy and carbon embodied. Thus, functional elements common to all typologies were chosen, with reference to UNI 8290-1:1981 "Residential building. Technological system. Classification and terminology" [19].

3.3 Characterization of technological units and functional elements

Technological characterization of the functional elements was carried out on the basis of a survey, carried out on the Cilento coastal territory (near Salerno-Southern Italy), of the most popular construction techniques in the last fifty years, by residential building typologies (Tab.1).

3.4 Quantification of functional elements

The tool used for the characterization and quantification of functional elements is Rhinoceros, 3D CAD modeling software, with which it is possible to create, modify, analyze and translate NURBS "Non Uniform Rational Basis Spline" curves, surfaces and solids, i.e., mathematical representations of 3D geometry used for the precision of curves and surfaces. Associated with this software was its Grasshopper plugin, an algorithmic modeling tool used to generate and control through parameters, complex shapes represented. The use of Rhino and its plugin, made it possible to obtain a graphical representation of the case studies, to be able to govern the chosen functional parameters and to extrapolate the quantities of each of them to be correlated, in the next step, to associated energy factors.

Table 1
Functional elements and construction technologies.

Classes of technological units	Technological units	Classes of technical elements	Construction technique
	1.1 Foundation structures	1.1.1 Direct foundations	Inverted beams and ventilated crawl space
1. BEARING STRUCTURE	1.2 Elevation structures	1.2.1 Vertical structures	Frame structure
		1.2.2 Horizontal structures	
	2.1 Vertical closures	2.1.1 Vertical perimeter walls	Infill with thermal coat
2. CLOSURES		2.1.2 External vertical frames	Single or double-hung windows
	2.4 Upper closures	2.4.1 Coverages	Flat roofing
	3.1 Vertical partitions	3.1.1 Internal walls	Brick partitions
3. INTERNAL PARTITIONS		3.1.2 Internal fixtures	Doors
	3.2 Horizontal partitions	3.2.1 Floors	Cement brick floors
	3.3 Inclined partitions	3.3.1 Internal stairs	Climbing slab stairs

3.5 Calculation of Embodied Energy and Carbon

Gli strumenti utilizzati per il calcolo dell'energia e carbonio incorporati sono:

1) Environmental Product Declarations (EPDs) [20];

2) The database "Inventory of Carbon and Energy" (ICE) [21], one of the most widely used in Europe, which, in a concise manner, collects an archive of Embodied Energy (MJ/kg) and Embodied Carbon (kgCO2e/kg) factors of the most common building materials, considering
the system scope from cradle to gate (C2G).

The total embodied carbon values were identified with the help of an additional plugin, Cardinal LCA, associated with Rhino and Grasshopper; this analyses the embodied impacts, expressing them in Global Warming Potential, using The Inventory of Carbon an Energy or The Embodied Carbon in Construction Calculator (EC3) as databases. In addition, the plugin offers the possibility of including embodied emission factors that are not present, through Environmental Product Declarations (EPDs). The quantification of embodied energy was obtained from the application of the following equation:

$$EE=\sum_{i=1}^{n} EEF_i * Q_i$$

where, EE: total embodied energy│EEFi: i-th embodied energy factor│Qi: i-th functional element quantity.

3.6 Form parameters

In order to assess the incidence of form, the following parameters were identified, chosen according to the analysed building typology and its main morphological characteristics (Tab.2):

Table 2
Significant parameters associated with each building typology.

Building typology	Independent parameters					Dependent parameters				
	Dimension X: Main horizontal dimension of the building base	Net floor height	Basic geometric shape	Number of aggregated housing units	Number of floors	Glazing ratio: window/wall ratio	Slenderness ratio: height/width ratio	Form factor: width/depth ratio	Compactness: external exposed surface/volume ratio	Partition density: ratio of linear quantity of partitions/gross surface area
Detached house	X	X	X			X	X	X	X	X
Townhouses	X	X		X		X	X	X	X	X
Multi-storey building	X		X		X	X	X	X	X	X

The classification into two groups (independent and dependent parameters) is necessary because of the correlation between some of them, which generates inconsistencies with the subsequent steps of the method. A model was developed for each of the three building typologies through the variation of these shape parameters, carried out in the following steps.

3.7 Sensitivity analysis of independent shape parameters

In order to assess the different impacts of shape parameters on output, a sensitivity analysis has been carried out, an analysis that aims to improve decision making through an assessment of the appropriateness of design choices and to identify the input parameters that are significant because they are more sensitive to achieving the output objective [22]. Such analyses can be carried out on two domains: global and local [23]: the former, which is more reliable, considers the entire input variation space, while the latter focuses on the effects of uncertain inputs around a point, called the base case. The use of the global domain can be associated with four

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different methods: regression, screening, variance and meta-modelling, as defined by Tian [24]. In accordance with the case histories under consideration, a screening method, Morris' method and, a variance method called Sobol's Indices was chosen.

3.7.1 Application of the Morris method

The ranges of independent shape parameter values, for each building typology, were applied according to the one-step-at-a-time (OAT) method (Tab.3). The variation of 5 scenarios, for each independent parameter, resulted in a range of Embodied Energy and Embodied Carbon values of the building under consideration, which could then be related through the application of the second step of the Morris method, i.e., calculation of mean and standard deviation.

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Table 3
Range of independent shape parameters for each building typology.

Building typology	Independent parameters	Range
DETACHED house	Dimension x	10m; 15m; 20m; 25m; 30 m
	Floor height	2.70m; 3.00m; 3.30m; 3.60m; 3.90 m
	Basic form	Square, Rectangle, Triangle; Circle; Exedra
TOWNHOUSES	Dimension x	10m; 15m; 20m; 25m; 30 m
	Floor height	2.70m; 3.00m; 3.30m; 3.60m; 3.90 m
	Number of residential units	2; 3; 4; 5; 6
MULTI-STOREY building	Dimension x	20m; 25m; 30m; 35m; 40 m
	Number of floors	2; 3; 4; 5; 6
	Basic form	Square; Rectangle; Triangle; Circle; Exedra

3.7.2 Sobol index method

In order to obtain further feedback on the results of the Morris method, a sensitivity analysis was carried out using the variance method through Sobol indices, measuring the variability of the absolute values of the Xi variable, i.e., how much they deviate quadratically from the arithmetic average. The purpose of sensitivity analysis is to determine how much, the variability of the output, depends on each of the input parameters. The outcome of the variance method is expressed in the form of percentage numerical values (Sobol indices): specifically, first-order sensitivity indices, or main-effect indices, were chosen. These determine the contribution, to the variance of the output, of the variance of each input parameter, taken individually, but averaged over the variances of the other inputs.

3.8 Evaluation of dependent form parameters

The application of the Morris method, as part of the OAT analysis, was based on the assumption, for each step, of designated ranges of values for the independent shape parameters; this consequently generated variation in the dependent shape parameters. The dependence of the latter on some of the independent parameters made it impossible to apply the two sensitivity analysis methods on this second group of variables as well. So, considering the very variability and dependence of these inputs, two other methods of comparison were chosen: the coefficient of variability and linear correlation.

3.8.1 Coefficient of variability

Quantitative variability was found in the cases under study, measured using indices based on the distance of modes from a position index. These indices are absolute or relative by virtue of their correlation with the unit of measurement of the phenomenon under consideration. Since dependent shape parameters are measured with different units, relative indices were considered. These have two main characteristics: they can take on only positive values, since the application of the variability index to a population with zero mean or variability would lead in the former case to an infinite value, in the latter the application itself would lose meaning; they take on increasing values as variability increases. In the field of relative indices, it takes on easy interpretation the coefficient of variation or variability, a dimensionless number, expressed in percentage terms, obtained from the ratio of standard deviation and arithmetic average. The choice to use this coefficient thus stems from the possibility of comparing dependent form parameters expressed in different units and relating their variability to the final output.

3.8.2 Linear correlation

Correlation expresses the tendency of two variables to change their value simultaneously. In this case, it is necessary to analyze the type and form of relationship existing between the variables. Regarding the type of relationship, we can have two cases: linear and nonlinear relationship. Regarding the form of the relationship, we need to evaluate its direction and magnitude. The direction can be positive, if both variables increase/decrease; negative, if one variable increases and the other decreases. The more clustered the values, the stronger the relationship; if the values are uniformly dispersed, the link is nonexistent. Application of the method revealed a linear-type relationship between the dependent shape parameters and the final output. Therefore, Pearson's correlation index, or linear correlation index, was identified, which can define the magnitude and form of the above relationship.

3.9 Parameters excluded from the investigation

The purpose of the study is to highlight the shape parameters that can direct toward sustainable design through reduction of embodied energy. Therefore, the parameters considered are the physical form factors of the investigated building typologies. For this reason, parameters that may influence the operational energy factor are not investigated, namely:

-external factors (orientation, solar radiation, ventilation, etc.);
-plant components (heating and cooling systems, etc.).

4. Application to Case Studies / Results

The typological analysis made it possible to identify the respective morphological characters and basic recurring geometric forms. From the typological characterization, shape parameters were extrapolated, allowing the development of the method with reference to the three prevailing building typologies: detached house, townhouses, multi-storey building. The development of the models was subordinated to compositional design choices in terms of basic form, interior divisions, number and size of windows, as well as the choices of construction technologies and materials described in the previous chapter. For brevity of discussion, the application development to townhouses (Fig.3) and multi-storey building typologies (Fig.4) are omitted.

Fig. 2. Detached houses typology in the Agropoli town, Salerno – Southern Italy

Fig. 3. Townhouse typology in the Agropoli town, Salerno – Southern Italy

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Fig. 4. Multistorey typology in the Agropoli town, Salerno – Southern Italy

4.1 Detached House

The detached house is one of the most widespread building typologies in the coastal territory of Southern Italy. Figure 2 shows two variants, identified in the territory of the municipality of Agropoli (Salerno-Southern Italy), whose typological characteristics were used to apply the methodology.

4.1.1 Model

The typological characterization data populated the initial model, on which all application cases were processed. After the model was processed, it was transferred to Rhinoceros software and its associated Grasshopper plugin (Fig.5). The use of the second Cardinal LCA plugin, conferred the opportunity to: quantify all the functional elements represented, match them to the associated emission factor, via the Inventory of Carbon and Energy (ICE) or the Environmental Product Declaration (EPD) and obtain the total embodied carbon values for each group of functional elements. Figure 6 shows the example for the "Vertical Elevation" class.

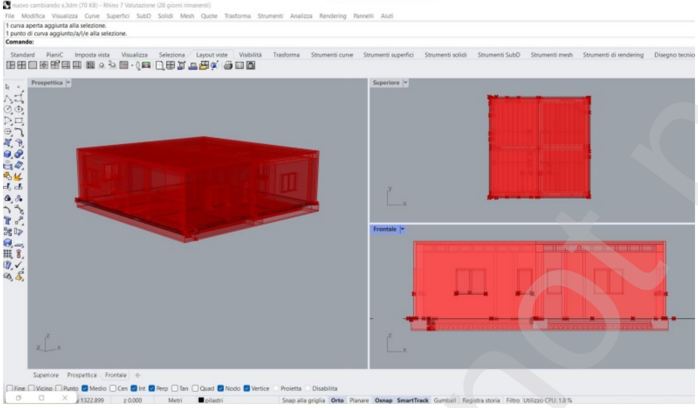
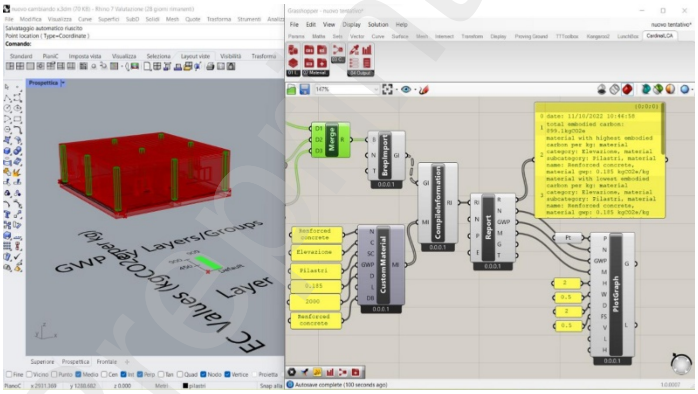


Fig. 5. Graphic rendering of the Detached house model on Rhinoceros



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0 date: 11/10/2022 10:46:58
1 total embodied carbon: 899.1kgCO2e
2 material with highest embodied carbon per kg: material category: Elevazione, material subcategory: Pilastri, material name: Renforced concrete, material gwp: 0.185 kgCO2e/kg
3 material with lowest embodied carbon per kg: material category: Elevazione, material subcategory: Pilastri, material name: Renforced concrete, material gwp: 0.185 kgCO2e/kg

Fig. 6. Application of Cardinal LCA for the class of functional elements.

The Embodied Carbon results for each class of functional element, extrapolated from the software, were reported in an Excel spreadsheet to determine the Embodied Energy values for each class of functional element. On the same sheet, the total values of Embodied Carbon (Fig.7) and Energy (Fig.8) for the model under consideration were also computed. Based on these data, a twofold comparison of the functional element classes was made to identify the most energy- and emission-intensive.

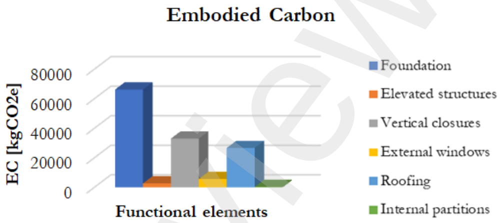

Fig. 7. Comparisons of EC values, relative to functional element classes for the Detached House model

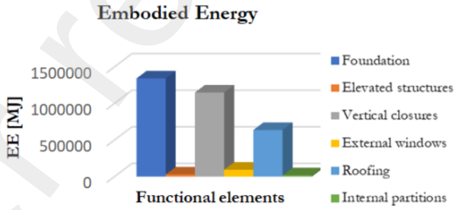

Fig. 8. Comparisons of EE values, relative to functional element classes for the Detached house model

Table 4
Invariant characteristics of the one-step-at-a-time (OAT) analysis on the shape parameter "Dimension x" for the Detached house

Invariant characteristics	Dimension y Floor height Number of levels	10 m 2.70 m 1

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Table 5
Summary of shape parameters obtained by varying the "Dimension x" parameter and the respective EC and EE values.

Dimension x (m)	Glazing ratio (%)	Slenderness ratio	Form factor	Compactness (m2/m3)	Partition density (m/m2)	EC factor (kgCO2e)	EE factor (MJ/kg)
10	6.73	0.31	1	1.04	0.34	134939	3268480.6
15	7.31	0.21	1.5	0.97	0.34	190714	4562417.0
20	7.69	0.16	2	0.94	0.34	245934	5836585.0
25	7.97	0.13	2.5	0.92	0.34	301153	7110742.6
30	8.17	0.10	3	0.91	0.34	356373	8384910.5

4.1.3 Results obtained by varying the parameter "floor height"

For the "floor height" parameter (starting from the threshold imposed by the Italian DMS July 5, 1975) the range of values was assumed by increasing, for each step, 0.30 meters. The invariant characteristics are shown in Table 6 and the results in Table 7.

Table 6
Invariant characteristics of the one-step-at-a-time (OAT) analysis on the shape parameter "floor height" for the Detached house building typology.

Invariant characteristics	Dimension y	10 m
	Number of windows	4 with one door and 5 with two doors
	Number of levels	1
	Dimension x	10 m
	Basic form	Square

Table 7
Summary of shape parameters obtained by varying the "floor height" parameter and the respective EC and EE values.

Dimension x (m)	Glazing ratio (%)	Slenderness ratio	Form factor	Compactness (m2/m3)	Partition density (m/m2)	EC factor (kgCO2e)	EE factor (MJ/kg)
2.70	6.73	0.31	1	1.04	0.33	134939	3268480.6
3.00	6.14	0.34	1	0.98	0.33	139109	3411700.5
3.30	5.65	0.37	1	0.94	0.33	142700	3534870.6
3.60	5.22%	0.40	1	0.90	0.33	146291	3657973.1
3.90	4.86	0.43	1	0.86	0.33	149882	3781075.6

4.1.4 Results obtained by varying the parameter "Basic shape"

The third independent parameter, used for the OAT design of the Detached house typology, is "Basic Shape." The choice of this parameter, although in the area under study the Detached house predominantly has a quadrangular plan, was dictated by the possibility of making the model applicable to possible additional and different case studies. For this parameter, the range chosen is not numerical in nature, but 5 simple geometries were identified, which are in any case usable in the built environment and already listed in Table 3. The invariant features identified in this step are shown in Table 8.

Table 8
Invariant characteristics of the OAT analysis on the "Basic shape" shape parameter for the Detached house building typology

Invariant characteristics	Number of windows	4 with one door and 5 with two doors
	Number of levels	1
	Floor height	2.70 m
	Dimension x main	10 m

As an example, the application with a basic form in Exedra is shown. This shape was constructed by starting from the square geometry of the model and inserting a hemicycle element (Fig. 9). The invariability of the parameter "Dimension x" was ensured by setting the maximum distance between two opposite facades in both x and y directions equal to 10 meters.

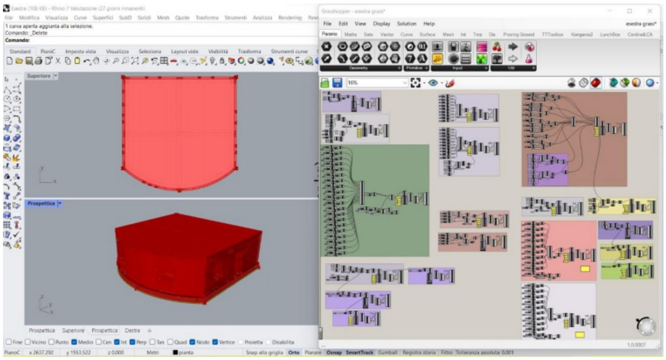

Fig. 9. Graphic rendering of Detached house - "Basic shape": Exedra

Table 9
Dependent shape parameters Detached house – "Basic shape": Exedra.

Dependent shape parameters	
Glazing ratio	7.35%
Slenderness ratio	0.31
Form factor	1
Compactness	0.71
Partition density	0.40

Table 10
Summary of dependent shape parameters by varying the "Basic shape" parameter and the respective EC and EE values.

Basic form	Glazing ratio	Slenderness ratio	Form factor	Compactness	Partition density	Embodied Carbon	Embodied Energy
Square	6.73%	0.31	1	1.04 m2/m3	0.33 m/m2	134939 kgCO2e	3268480.6 MJ
Rectangle	7.31%	0.31	0.67	0.97 m2/m3	0.34 m/m2	190714 kgCO2e	4562417.0 MJ
Triangle	8.14%	0.31	1	1.30 m2/m3	0.45 m/m2	61462 kgCO2e	1612650.6 MJ
Circle	4.29%	0.31	1	1.44 m2/m3	0.49 m/m2	94506 kgCO2e	2325905.1 MJ
Exedra	7.35%	0.31	1	0.71 m2/m3	0.40 m/m2	124844 kgCO2e	3029261.4 MJ

Table 9 shows the dependent form parameters of the Isolated house typology - with reference to the "Basic Form" Exedra. Table 10 shows the summary of the dependent shape parameters as the "Basic Form" parameter changes, as well as the respective values of EC and EE.

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4.1.5 Application of the Morris Method to the building typology: Detached house

Analysis of the case studies by varying the independent shape parameters using the OAT design enabled the first stage of the Morris method to be fulfilled. The second stage, i.e., comparison between case studies necessitated the calculation of arithmetic average and standard deviation of the overall values of Embodied Energy and Embodied Carbon, identified by the independent shape parameters. These values, shown in Table 11, represent the Cartesian coordinates of the points obtained with the Morris graphical representation (Figures 10,11).

Table 11
Arithmetic average and Standard deviation Embodied Carbon and Energy

Independent shape parameters	Embodied Carbon		Embodied Energy	
	Arithmetic average	Standard deviation	Arithmetic average	Standard deviation
Dimension x	245822.6	87485.7	5832627.1	2020892.5
Floor height	142584.2	5863.8	3530820.1	201136.5
Basic form	121293.0	48258.1	2959743.0	1105115.8

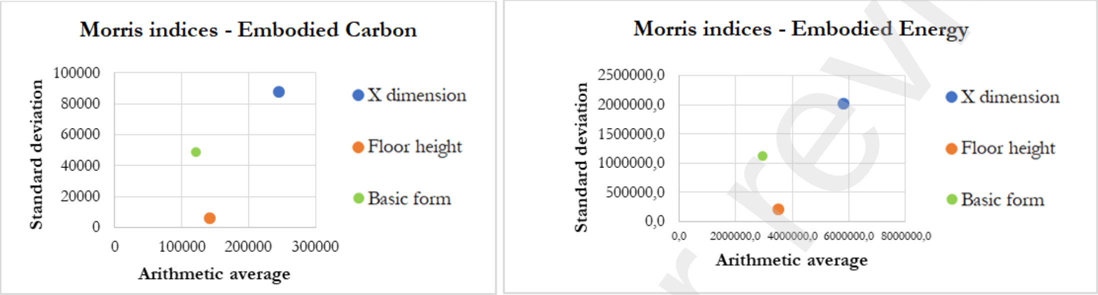

Fig. 10,11. Graphics representation of the Morris Embodied Carbon (on the left) and Embodied Energy (on the right).

The sensitivity analysis developed through the Morris method has the advantage of immediate decoding of the results, as the graphical representation is immediately understandable. From this initial analysis, it was deduced that, for the Detached house building typology, the shape parameter that greatly influences the amount of embodied Energy and Carbon is the "x Dimension."

4.1.6 Application of the variance method "Sobol indices" to the building typology: Detached house

In order to obtain further feedback in terms of the sensitivity of the parameters, the variance method was applied, through the definition of Sobol's Indices; hence, the required statistical quantities, i.e., the variances of the i-th parameters and the total variance, were calculated for Embodied Carbon and Embodied Energy, the values of which have been reported in Table 12. The graphical rendering of this method, in Figures 12 and 13, was made using histograms; this choice was dictated by the readability of this representative typology.

Table 12
Variance and Indices of Sobol Embodied Carbon and Energy – Detached house.

Independent shape parameters	Embodied Carbon		Embodied Energy	
	Variance	Sobol index	Variance	Sobol index
Dimension x	7653746764	76.41%	4084006591442.8	76.40%
Floor height	34384439.7	0.34%	40455894081.5	0.76%
Basic form	2328847522	23.25%	1221281033367,7	22.85%
Total values	10016978726	100%	5345743518891.9	100%

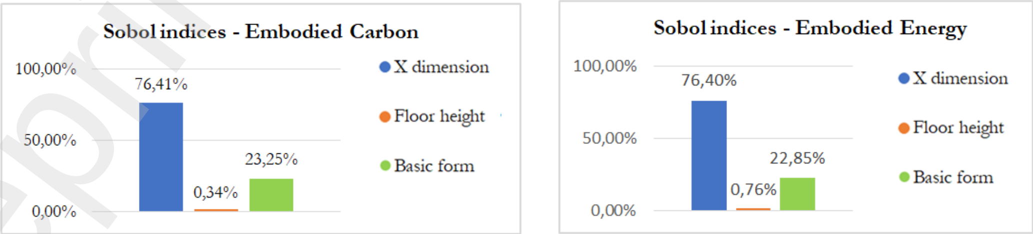

Fig. 12,13. Graphic representation of the Sobol Indices, Embodied Carbon (on the left) and Embodied Energy (on the right).

The insights obtained from this second sensitivity analysis reconfirmed what was inferred from the Morris method, namely, the clear superiority of the independent shape parameter "Dimension x" over the others considered.

4.1.7 Evaluation of dependent form parameters in each macro case of the building typology: DETACHED house

The one-step-at-a-time (OAT) analyses determined the variation, one by one, of the dependent shape parameters. To assess this variability and to be able to compare these parameters, expressed in different units

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of measurement, the relative variability index, or "Coefficient of Variability," is used. Similar coefficients were calculated for each macro-case so that, based on the results obtained in the sensitivity analyses, an additional clue could be obtained as to how much each parameter and its variability may affect the final output (Table 13). In macro-case 1, the most variable dependent shape criteria are the Slenderness Ratio and the Form Factor; in macro-case 2, the change in the "Floor Height" parameter did not result in any change in the Shape Factor and Partition Density criteria, in fact the coefficient of variability is zero, so these parameters cannot influence the final output, while the Glazing Ratio and the Slenderness Ratio are the most influential; in macro-case 3, related to the parameter "Basic Shape," the two criteria with a higher coefficient of variability were found to be Compactness and Glazing Ratio.

Table 13

Coefficients of variability in the three macro cases of the Detached house.

Coefficients of variability	Dimension x	Floor height	Basic form
Glazing ratio	7.55%	12.93%	21.76%
Slenderness ratio	45.91%	12.75%	0.29%
Form factor	39.53%	0 %	15.97%
Compactness	5.56%	7.46%	26.19%
Partition density	1.14%	0 %	16.59%

In order to study the extent of the dependence of these shape parameters on the independent parameters and intrinsically on the outputs of the analysis, the typology of their relationship was identified, which was found to be linear, both with respect to the values assigned for each step to the independent shape parameters and with respect to the total amounts of carbon and energy incorporated, in all three macro cases. The dependence was represented in a single graph, shown in Figure 14.

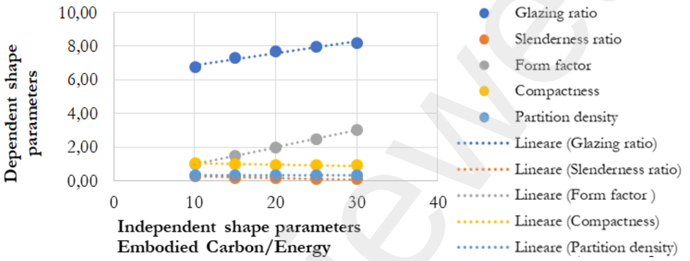

Fig. 14. Linear relationship between shape parameters and embodied Carbon and Energy – Detached house

Once the linearity of the relationships was demonstrated, we proceeded with the calculation of the linear correlation coefficient, chosen to study the extent of the dependence of the parameters under examination (Tables 14-15).

The results highlighted that the typology and entity of the linear correlation varied in each case study, with the exception of Compactness, which was always inversely correlated to the independent shape parameters and the overall values of Embodied Energy and Carbon.

Table 14

Linear correlation in the three macro cases of the building typology – Detached house.

	Linear correlation		
	Macro case 1: Dimension x	Macro case 2: Floor height	Macro case 3: Basic shape
Glazing ratio	0.98	-1.00	0.08
Slenderness ratio	-0.95	1.00	-0.80
Form factor	1.00	X	-0.80
Compactness	-0.95	-1.00	-0.58
Partition density	0.55	X	-0.79

Table 15

Typology of proportionality and linear correlation of the dependent shape parameters in the building typology - Detached house.

Detached house	Typology of correlation			Amount of correlation		
	Macro case 1: Dimension x	Macro case 2: Floor height	Macro case 3: Basic shape			
Glazing ratio	+	-	+	Strong	Strong	Weak
Slenderness ratio	-	+	-	Strong	Strong	Strong
Form factor	+	0	-	Strong	Absent	Strong
Compactness	-	-	-	Strong	Strong	Strong
Partition density	+	0	+	Moderate	Absent	Moderate
Legend:	(+) : Direct correlation		(-) : Inverse correlation		(0) : Zero correlation	

	Detached house	Townhouses	Multi-storey building
Embodied Carbon [kgCO2e]	134939	529580	866575
Gross volume [m3]	312	1881	3748
EC factor per unit volume [kg CO2e/m3]	432.5	281.5	231.2

The results highlighted that the typology and entity of the linear correlation varied in each case study, with the exception of Compactness, which was always inversely correlated to the independent shape parameters and the overall values of Embodied Energy and Carbon.

5. Discussions of Results

To make the building the gross volume unit, defined by urban planning regulations as the volumetric footprint in the space occupied by the shape of the individual building. This comparison was initially designed on the starting models of the three building typologies (Tab.16) and was repeated similarly for embodied energy.

Table 16

Comparison between building typology models – Embodied Carbon.

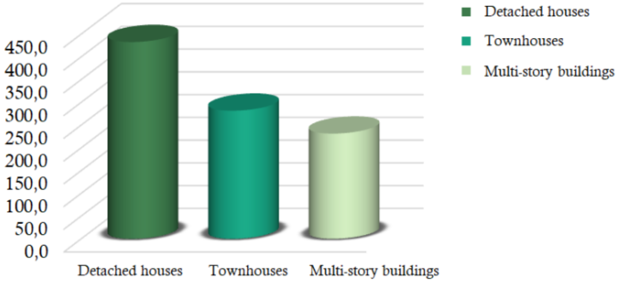

Fig. 15. Comparison between building typology models – Embodied Carbon

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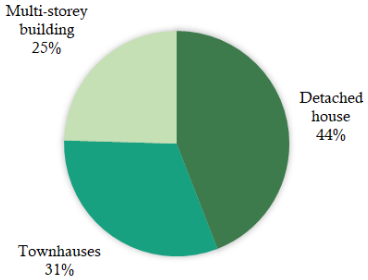

Fig. 16. Percentage incidence of each building typology in terms of Embodied Carbon

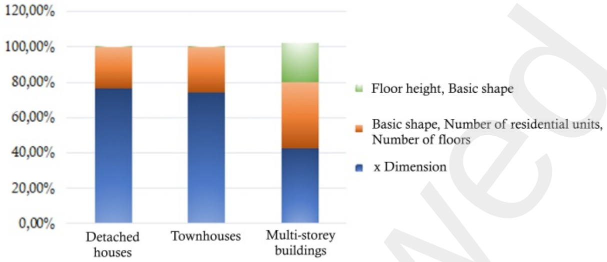

Fig. 17. Comparison of the sensitivity analyzes of the three building typologies – Embodied Carbon

From the first comparison it emerged that, although the detached house model generates a lower quantity of embodied carbon and energy, in absolute value, normalizing the results to the respective functional unit (m3) turns out to be the typology with the greatest environmental impact (Fig.15). While, the graph in Figure 16 shows the percentage incidence of each building typology in terms of Embodied Carbon.

The application of the method highlighted a dual outcome: testing the feasibility and correctness of the developed methodology and obtaining feedback for each chosen building typology and a comparison between them. By analysing each typology individually it was possible to delve deeper into the concept of shape for each of them and understand which characteristic, transformed into a shape parameter, was most sensitive to the final output, understood as the quantity of carbon and energy incorporated. The developed method is validated, as the sensitivity analyses conducted with the two methods, Morris and Sobol's Indices, identified the same most influential parameter, i.e., "Dimension x," understood as the horizontal development of the building. Only for the multi-storey building did this parameter find a sensitivity similar to another, namely the number of floors. The results, summarized in Figure 17, demonstrate that it is possible to reduce the EC and EE values by moving towards less influential shape parameters which, although increasing their value, do not generate a significant increase in emission levels. The introduction of dependent shape parameters has provided a further means to prevent the increase in the thresholds relating to each independent criterion: the designer can decide to intervene on the dependent parameters to compensate for the greater impact deriving from the increase in the independent parameters. The extent of the dependent shape parameters was found to vary depending on the building typology and the independent criterion to which they are associated; for which it was not possible to deduce a generalization, except for the Compactness parameter which was inversely correlated, in all cases, both to the independent parameters and to the quantities of energy and carbon incorporated. This gives an important clue useful for planning. Finally, the comparison between the building typologies led to the identification of the most expensive in terms of emissions and embodied energy, i.e. the detached house. This comparison made it possible to observe that, in an urban fabric, the construction of a multi-storey building or a row of buildings would lead to higher EC and EE values, but would provide better housing opportunities, allowing the construction of residences for a greater number of individuals.

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6. Conclusions

The objective of this study is to develop a methodology aimed at correlating building typology and embodied energy and carbon, in an attempt to compensate for a gap found in the scientific debate on low embodied carbon design. The design of NZEB buildings, with the reduction in OE, has resulted in the divarication of the range toward a relative increase in the EE factor.

For some years now, numerous scientific studies have addressed possible strategies for low-emission building design. These approaches have mainly considered the nature of materials as well as technological and structural aspects. Whereas, there does not appear to be as much attention paid to other parameters, such as the formal and typological parameters of the building, which can also influence the calculation of embodied emissions. The developed methodology was calibrated to three real case studies, i.e., three most common residential building typologies in a typical town in the Mediterranean area of southern Italy. Keeping constant the parameters already widely investigated (such as materials and construction techniques), the variables concern the formal parameters that distinguish the three building typologies under study: the x and y plan dimensions, floor height, total building height, glazing ratio, slenderness ratio, form factor, compactness factor, and partition density.

The method was developed at the building scale and can be applicable to any building. It has not been calibrated to be applied at the neighborhood or urban scale, as any adaptation of the model would involve the inclusion of additional parameters, extrinsic to the building, and related to the context, outdoor areas, infrastructure, etc.

The comparison of building typologies showed that the single-family house is the most EE and EC intensive typology, compared to multi-family typologies (townhouses and multi-storey building). This is evidently attributable to the compactness of the form and the optimization of technological components, which are common to several housing units.

The method appears to be validated, as sensitivity analyses conducted with the two methods, Morris and Sobol Indices, identified the same most influential parameter. The innovative aspects of the present study are:

1) investigation of an issue rarely addressed in scientific studies;

2) very few studies that address the issue (for ex.: Trigaux et al.), refer to abstract neighborhood models, not real cases (as in the present study).

It is believed that this study could have a significant impact, in terms of social, economic and environmental sustainability, by indicating guidelines for low-emission urban planning. In fact, the formal parameters that result in more sustainable design may be new parameters to be considered at the land-use planning stage.

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